N87-16394

# RELIABILITY AND ENGINEERING SCIENCES AREA

Materials Research: Single Junction Thin Film

Thin-Film Module Reliability Task

1. Hot-Spot Endurance of Amorphous-Silicon Modules

Part of the reporting period was involved in the design and fabrication of a new test bench for the purpose of improving control of hot-spot test accuracy.

Testing of the response of ARCO a-Si cells to back biasing was completed when two additional cells in a previously tested module were subjected to a 100-h cyclic hot-spot test. The hot-spot temperature reached a marginally acceptable value and the cells suffered the usual amount of erosion. Aside from this, no other changes were noted. A test performed to determine the relationship of the temperature of test cells in the ARCO modules to the temperature of the glass superstrate indicated that the difference is only on the order of a few degrees and less than the other uncertainties involved in the testing.

The hot-spot testing of Chronar submodules was completed. With cells in back bias and currents equal to those expected in a module cell string, the hot-spot temperatures usually did not exceed 120°C. The 100-h cyclic hot-spot test was performed on two Chronar modules. The test current was initially set to the module short-circuit current, which was deemed the appropriate current for performing the test. It was difficult to find cells with a back-bias voltage high enough to provide a power dissipation leading to a significant hot-spot temperature. The cells in the Chronar module had a lower breakdown voltage than the cells in the previously tested submodules. Also, the cells in the module exhibited a downward drift in current as the test progressed. As a result of the above factors, the power dissipation obtained in the cells tested was not enough to produce a hot-spot problem.

Many cells in a Solarex test structure were tested. The response of the cells was similar to that of the cells in the ARCO submodule previously tested.

Cells in a Sovonics module were tested and found to be very sensitive to back biasing with one of the cells becoming shorted in the initial phases of testing. Otherwise, the second-quadrant responses obtained for the cells were similar to those obtained for the ARCO Solar amorphous cells, once the cells stabilized after exhibiting rapidly changing characteristics. The overall effect was the dichotomous behavior observed in previously tested ARCO cells. The initial voltage breakdown occurred at about 8 V, with current runaway, followed by a much lower shunt resistance upon subsequent back biasing than originally exhibited. The Sovonics cells exhibited an even greater lowering of the shunt resistance than the ARCO cells. One of the cells exhibited a very erratic behavior, starting out like a previously untested cell, but then changing suddenly to a lower shunt resistance. After additional power dissipation, it changed back to its initial second-quadrant curve. Two of the cells exhibited the low shunt resistance behavior characteristic of amorphous cells that have already been back biased. In these two cases, the back

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biasing occurred as the test was initiated. Apparently, the cells suffered from some transient voltage surge occurring at the onset of testing.

The rate of change of temperature with power dissipated ranged from about 6°C to about 18°C/W. These results are within the range of those obtained for the ARCO amorphous cells. The Sovonics modules have a short-circuit current of about 2.75 amps. In the high shunt resistance mode, that amount of current was enough to produce hot-spot temperatures exceeding 140°C in one of the cells tested. Another cell, however, had multiple hot-spots. During the period of testing, the dominant hot spot (one with highest temperature) alternated among the ones in existence until there were two at the same temperature. At this point, it took about 3 A of power dissipation to reach a temperature in excess of 140°C. Apparently, the hot spots were sharing the power dissipation evenly, requiring more total power dissipation to reach a given hot-spot temperature.

The only visible effect noted during the testing was a small blister around one of the hot spots. The hot-spot temperature of the cell did reach in excess of 170°C, at which point the test was terminated. The back-bias current was equivalent to the short-circuit current produced by a Sovonics module, and the voltage was equivalent to that of two series cells. Therefore, based on this result, the use of bypass diodes around every one or two cells seems rational.

A major portion of the amorphous-cell hot-spot testing was summarized in a paper, titled Hot-Spot Durability Testing of Amorphous-Silicon Cells and Modules, by C. Gonzalez and E. Jetter. It was presented at the 18th IEEE Photovoltaic Specialists Conference in Las Vegas, Nevada, in October 1985.

2. Electrochemical Corrosion of Amorphous-Silicon Modules

Electrochemical corrosion research focuses on corrosion mechanisms to which both crystalline and a-Si modules may be subjected in central station applications, on the determination of corrosion rates, and on the ascertainment of means of corrosion passification. Corrosion mechanisms and rates have been previously determined and reported, so the present objective is to study the details of the corrosion processes and to develop passification design strategies.

It has previously been determined that module leakage currents are responsible for observed electrochemical corrosion. An experiment called SVI has revealed the detailed nature of module leakage-current behavior. Encapsulants polyvinyl butyral (PVB) and ethylene vinyl acetate (EVA), sandwiched between symmetric cylindrical brass electrodes with guard rings, were mounted on glass and subjected to a broad range of controlled temperature/humidity environments. Bulk, surface, and interfacial electrical conductivities were frequently monitored. It was determined that surface currents are relatively small, and that the encapsulant/glass interfaces support the highest levels of leakage current.

In a related experiment called CHRNRI, Chronar-supplied, self-laminating, substrate films have been mounted to glass substrates upon which 200 Å Ti-Ag cylindrical electrodes with guard rings have been vapor deposited. The critical interfacial conductivities are presently being monitored for this amorphous-module-like sample configuration.

In yet another experiment called BEMCOVSI, glass-mounted EVA sample is undergoing exposure to an 85°C/10% relative humidity (RH) environment while being exposed to 1 sun of UV radiation. During the initial 1000 h exposure period, interfacial, bulk, and surface currents have remained steady. The interfacial current is 10 times higher than the surface current while the bulk current is intermediate.

### 3. Solar Cell Reliability Testing

At Clemson University, research has continued on performing tests that will lead to identification of degradation mechanisms in thin-film cells. Work has been completed on developing stress-testing procedures, specifically for a-Si cells. Much of the effort went into developing a measurement system for accelerated testing of a-Si cells with a repeatability of 1%.

A variety of cells (including encapsulated and unencapsulated, and single-junction and tandem-junction) and several designs have been subjected to accelerated stress tests, in which the parameters are test time, temperature, illumination, and open- or short-circuiting. Most cell samples have been supplied by ARCO Solar, Inc., Chronar Corp., Solarex Corp., and Sovonics Solar Systems. From physical observation of cells that have degraded during these tests, it appears that irreversible degradation at elevated temperatures is the result of a solid-state reaction between aluminum and a-Si films.

### 4. Module Reliability Testing

The determination of humidity degradation rates and the identification of key electrochemical failure mechanisms continued for generic module designs based upon temperature/humidity testing cycles and data from solar radiation surface meteorological observations (SOLMET) weather tapes. Thirty-six modules, including amorphous, EFG ribbon, dendritic web ribbon, and Cz types, were under long-term exposure at 85°C/5% RH and 85°C/85% RH with 15 V and 250 V on selected samples for evaluating sensitivity to electrochemical degradation. Inspection periods of 10, 20, 45, 90, and 180 days were scheduled and included electrical (I-V curve) and visual performance data. Significant 40-day results included series resistance increases and power losses for shorted cell string a-Si modules in 85°C/85% RH over 85°C/5% RH environments and visual electrochemical degradation for print-Ag Cz cells in glass-EVA-Tedlar and glass-aliphatic polyurethane-glass module types exposed to 85°C/85% RH and a 250-V bias between shorted cell string and frame. This degradation, however, resulted in minor peak power losses of less than 5%. Further, the 40-day performance results for the Cz modules were consistent with goals established for 20-year field equivalent transmissivity and series resistance values obtained from previous testing. Consequently, the long-term tests were not continued beyond day 40.

Field tests initiated in June through August 1985 on several a-Si submodules with samples short-circuited, open-circuited or under Zener-diode loads, simulating maximum power loading, resulted in significant power degradation for all modules. This led to a new series of accelerated field tests to evaluate the effects of temperature and possible annealing while the submodules are under Zener-diode loads, simulating maximum power loading. Back-surface heaters to maintain a constant (24-h) temperature or cyclic a.m. (8:00 to 5:00 p.m. daily) temperature were installed on several samples and set at 70, 85, and 100°C levels. Visual inspection and electrical performance measurements were scheduled at 2, 4, 10, 20, 40, 80, and 160 days of exposure. To date, the cycled modules have completed 80 days of testing and I-V curve comparisons have shown progressive decreases in shunt resistance levels resulting in average peak power losses up to 26.8% for 80°C samples, and 39.7% for 100°C samples. The next scheduled inspection period is in June 1986 and may identify a further separation in results for the 85 and 100°C levels. The continuous heating samples have completed 40 days of exposure and are being compared with the cyclic sample results at 85 and 100°C levels. After 22 days, the 100°C module cracked severely during a rain shower and was removed from the test. Comparative data should be completed in May after the day 80 inspection period.

5. Thin-Film Module Development

Hughes Aircraft Company completed deliveries of 4 x 1 ft modules that consisted of an encapsulated and framed assembly of Chronar submodules. These modules were subjected to the standard Block V qualification tests to determine what further work was needed in increasing the reliability of a-Si modules. It was clear from the tests that further development should be performed at the submodule level to optimize the package design while obtaining the desired reliability. A contract, therefore, was undertaken with Chronar Corp. for a program of material selection, module design, module fabrication, and module test. As part of this effort, module assemblies of diverse types have been supplied to JPL for testing. These are being subjected to some of the standard qualification tests and to special field tests. Also, samples of module materials are being subjected to environmental stress tests and other studies.

Modules have also been obtained again from ARCO Solar, Inc., Solarex Corp., and Sovonics for special field tests, some standard qualification tests, and special stress tests and studies.

The problem of module development was also attacked by exploratory development of module encapsulant systems. The approach taken consisted of formulating concepts for thin-film encapsulation and generating an initial description of thin-film encapsulation construction elements. This route was patterned after the approach taken in 1977. Construction elements for crystalline-silicon solar cell modules were then generated, leading to the identification of EVA as an encapsulant.

For a thin-film glass superstrate design, the rear surface to be protected by encapsulation is considered to be aluminum. A key requirement, therefore, is to prevent aluminum corrosion. Thus, for the construction elements, the first layer against the aluminum is considered to be a chemical coupling agent. It may be based on organosilane chemistry that functions doubly as an anticorrosion agent and a chemical bonding agent. The next layer could be a pressure-sensitive adhesive to permit instant adhesion during manufacturing. This layer must later cross-link to work efficiently with the chemical coupling agent. The last layer is a mechanically durable back-cover plastic film, with the initial choice being fluorinated ethylene propylene (Teflon FEP Du Pont).

As practiced in the thin-film manufacturing process, a final step is to heat the module at 100°C for a period of time specific to each manufacturer. This time is generally longer than 1 h. The cross-linking reaction required for the adhesive layer could be made to occur during this thermal process. The adhesive could also contain the coupling agent as a compounding ingredient. Thus, bonding to the aluminum and adhesive cross-linking could be accomplished simultaneously.

The above approach uses dry films and pressure-sensitive adhesives to satisfy the construction elements, but the same could be accomplished with liquid casting systems. These could be deposited, for example, by curtain coating, as part of an in-line total manufacturing operation. Initially, arcylic and EVA chemistries will be explored for pressure-sensitive adhesives, and urethane chemistries will be emphasized for the liquid systems.

For a substrate design, construction elements are viewed as being a transparent top cover plastic film, with an adhesive lower layer for bonding to ITO, or other electrically conductive transparent material. There is a current awareness that thin-film modules using a-Si apparently suffer a reduction in power output, which on speculation may be related in part to exposure to light. If true, it can be conjectured that UV light up to 360 nm may be involved, since these wavelengths can cause photodegradation of polysilanes. Thus, if it is ever found that UV affects a-Si, then the outer cover plastic film would have to be UV-screened, up to the limit of the offending wavelengths.

If UV-screening is not needed for a-Si protection, the most viable top cover candidate is Teflon FEP-C (Du Pont), in combination with a virtually weatherable acrylic adhesive. One of the key material challenges appears related to bonding the adhesive to ITO, or its equivalent.

From EVA weather stabilizer studies, the experimental aging of advanced EVA formulations with low-molecular-weight and high-molecular-weight hindered amine light stabilizers (HALS) is beginning to indicate that long-term EVA stabilization is better served with low-molecular-weight HALS. This family of compounds provides protection against UV-photooxidation. It is speculated that the low-molecular-weight HALS has greater mobility within the bulk EVA, and is thus able to diffuse more readily to EVA sites undergoing UV-photooxidation. The high-molecular-weight HALS, however, would diffuse more slowly, if at all, and this may limit its capability to respond to localized sites of EVA photooxidation. An initial reason for investigating high-molecular-weight HALS was to guard against the potential for physical loss by migration or evaporation, a concern with low-molecular-weight compounds. The current experimental trends suggest that an optimum molecular weight may be needed to maintain sufficient diffusion for protection, while minimizing the potential for diffusion-related physical losses.

In any event, the current commercial choices are Tinuvin-770 (a low-molecular-weight HALS), and Cyasorb UV-3346 (a high-molecular-weight HALS). The trend currently favors Tinuvin-770. There clearly is a need to develop an intermediate-molecular-weight HALS.

Aging of fully compounded and weather-stabilized EVA strongly suggests that this material may not need the additional protection of a UV-screening top cover film. The need for a UV-screening film was conceptualized early in the FSA program, but experimental evidence is suggesting otherwise. If true, this would permit the use of Teflon FEP-C as an outer cover film. This non-UV-screening film is known to be a naturally weatherable material.

The aging of test specimens of Teflon FEP-C over A-9918 EVA on the outdoor heating racks, and in the RS/4 UV acceleration chambers, was initiated this year. At this writing, the samples have been aged more than 4000 h, with no problems. This encouraging testing will continue as long as possible.

Addressing the problem of flammability, Springborn developed a curable and processable, 18-mil-thick, non-flammable, EVA lamination film to be used in replacement of the conventionally clear EVA film which is positioned behind the solar cells. Preliminary module testing at UL indicated no positive improvements, as well as no negatives. It is necessary to conduct more testing and to modify PV module designs to more efficiently utilize the features of this new material. Interestingly, this new material is promising as a nonflammable gasket material for PV modules, but this application has not yet been tested.

This new material has a very high oxygen rating value of nearly 48%. This is the percentage of oxygen required in an atmosphere in order for this material to just sustain a flame. The material cannot be ignited, even in a direct flame, in a normal atmosphere of 20% oxygen.

6. Reliability Prediction and Management

One of the activities under this task was the development of software for the prediction of power loss resulting from open circuits in an array field of a-Si modules. Debugging of the software was suspended at that point to attend to more pressing matters.

The major activity for this reporting period was the preparation and initiation of combined environmental tests in a Bemco oven containing a controlled temperature and humidity environment and an UV lamp. The initial phase consisted of the design and fabrication of test fixtures and measurement apparatuses in support of the environmental testing. The most notable of these is a fixture for obtaining a-Si-cell I-V curves in the JPL large-area pulsed solar simulator (LAPSS).

The Bemco oven is an air-interchange, heat-and-refrigeration unit with a temperature range of -40 to 175°C and varying humidity (10 to 100%). The oven has a 2000 W medium-pressure-mercury UV lamp capable of putting out one to two suns of UV radiation at a distance of 40 cm from the lamp.

Much of the activity in the early stages of the test was concerned with the shakedown of the system and the solution of a number of attendant problems occurring in the system. The UV-lamp cooling system was converted to all stainless steel as a result of deposits on the glass cooling jacket surrounding the lamp. Another problem, involving the oven microprocessor/controller, resulted in erratic control of the oven parameters after a power outage and subsequent reprogramming of the controller. After consultation with the manufacturer, modifications were made that resolved the problems.

The following types of samples are being tested in the oven: 1.9 x 10.2 cm strips of module encapsulant and cover materials, 10.2 x 10.2 cm laminated Tedlar-EVA-glass coupons, 10.2 x 10.2 cm a-Si submodules (some with a Tedlar front cover), and other assorted samples.

Measurements of the UV radiation have been made using a photocell radiometer and chemical actinometers. The use of radiometers will be expanded over the initial limited use when the entire Bemco system is mated to a computer allowing frequent precise measurements to be made. The use of actinometers is being phased out. Spectral-radiometric measurements will be made with a monochromator.

Several sample physical parameters were measured during the first three months of testing, about 8 weeks of actual oven-running time. One of these, sample weight loss, is a measure of the loss of additives, absorbers, and screening agents. Losses of up to 1.35% were measured for the samples exposed in the Bemco. The combination of weight loss measurements and transmission measurements in the UV range (the latter is discussed below) imply the loss of UV screening agents. Several Tedlar samples were exposed in a dry oven (no UV) and a vacuum oven (no UV) for 500 h. The weight loss of the samples in the dry oven was approximately equal to the weight loss of similar samples in the Bemco oven for the same period of time, while the weight loss of the samples in the vacuum oven was greater. This implies that the mechanism for loss of the screening agents is related more to the thermal environment than to the UV radiation.

The sample transmission measurements at 400 nm showed gains from a few percent to 15%, with a loss in transmission becoming apparent at higher wavelengths. The change in transmission seems to have stabilized. The interpretation of these results is that the sample exposure time was long enough to result in loss of the UV screening agents, but not long enough to result in the loss in transmission that is expected to occur with time at 400 nm.

The "push test" developed at JPL, using a steel-ball push device, was used to test several laminated-Tedlar-front-cover samples. The device is used to depress the Tedlar through the application of a force through the steel-ball-tip (1/16 in. diameter). When this test was applied to the modules with a Tedlar front cover that had shown severe cracking when exposed at the Southwest Residential Experiment Station, the Tedlar cracked and revealed its embrittlement. When the test was performed on samples removed from the oven (7 weeks of exposure) no cracking developed and the materials appeared to retain their ductility. The cumulative exposure time in the oven by the end of the reporting period was not long enough to cause the deterioration noted in the field.

The I-V curves of the cells in a Chronar a-Si submodule were measured after 3 weeks of exposure. Two cells showed an increase in max-power. The rest showed a loss, with the average of all losses being 11%. The cells in an ARCO a-Si submodule were measured after 3 weeks of exposure and showed an average max-power loss of 19%.

7. Module Failure Analysis

Failure analysis continued on four ARCO Solar Genesis modules. Each of the modules had a severely warped frame that was displaced from its original position about the edges of the module. The two cells on each module with a border on the module edge were found to have a large fraction of their surface areas shadowed by the distorted frame. The frames were removed, and the modules were reflashed at the LAPSS. Power on two of the modules was completely recovered, while power on the other two modules was only partially recovered, with about 10% power loss remaining.

A Hughes Aircraft Corp. PV module (S/N KPOH 06) was received on July 2 with a reported 47% power loss after 37 thermal cycles. It was found that only six of the 12 cell strings contributed to module power. This module consists of four Chronar amorphous submodules which are arranged in parallel. The reported 49% power loss, found by shadowing tests, was caused by the failure of six of the 12 strings to contribute any power. Further testing showed that the strings were intermittent, with any given string sometimes contributing power and sometimes not, even though the module had not been stressed thermally or mechanically at any time. It is found, however, that two of the strings consistently failed to contribute any power. Interior examination showed an open-circuit condition between the negative terminal column tie copper strip and the cell adjacent to it, for each of the two failed strings. For some strings, $I_{SC}$ was found to decrease with increasing temperature, indicating an increasing series resistance as the temperature is increased. All evidence leads to the conclusion that the solder joints are defective that join the column tie copper strips to the adjacent cells.

Two submodules (KAOH-3 and KAOH-5) from Chronar were received at the failure analysis lab on August 8 with a reported open-circuit condition after environmental test (HF-10) at JPL. The module consists of 84 cells: 28 cells in series and three cells in parallel. Close examination by the curve-tracer indicates that more than one cell of each string was completely open. The locations of the reported open-circuit conditions have been determined. For each module, electrical continuity was observed between the column tie copper strips and adjacent cells. The sources of the open circuits were found to be across the cell interconnect regions within the thin-film layer. KAOH-3 was examined in detail, and it was found that nearly all cells examined exhibited highly resistive ohmic behavior (usually megohm range) across the transparent conductive oxide (TCO) scribe line. Energy-dispersive spectroscopy (EDS) of the inside surface of the two samples of the back side layer of paint showed an elemental distribution matching that of the complementary thin-film layer. To obtain the observed elemental distribution, the adhesion of the back side of the thin-film layer and the paint must have been strong enough to produce an uneven, yet clear fracture of the thin-film layer upon delamination or tangential strain of the paint.

Integrity of the cell string continuity was examined on one of the Chronar modules that has no back cover. Shunt resistance of the individual cells was compared with the pinhole density of the individual cells. Preliminary results indicate that the shunt resistance of an individual cell is closely related to the pinhole density.

Close examination of the whisker signal of the solar cell laser scanner (SCLS) on a-Si modules has revealed that the signal is clearly modified, even though the modulation was small when it was processed by electric amplifying circuits. To analyze the whisker signal of the SCLS on an a-Si module, the risetime and decay time of the laser scanner light source measured by a fast risetime photodiode were compared with those of the response time of the a-Si thin-film modules (Sanyo 7703-2). The risetime of both the laser scanner light source and the response time of the a-Si module is 1.0 ms, and the decay time of the thin-film module is 20 times longer than the light source, which is of the same order as the risetime. This may mean that the carrier transit time of the device causes the whisker signal before the initial carriers reach equilibrium with the recombination and/or trap centers of which decay time is longer than the transit time.

Feasibility of on-line computer analysis of the SCLS data and the sun-u-later data was tested by connecting them to the analog-to-digital converter of the DECLAB-23 of the Digital MNC System. The plotting p gram of the display of the SCLS was found useful.

During this report period, a paper entitled "Effects of Excitation Intensity on the Photocurrent Image of Thin-Film Silicon Solar Modules," by Q. Kim, A. Shumka, and J. Trask, has been accepted to be published in Solar Cells in 1986.

Systems Research

Crystalline-Silicon Module Reliability Task

1. Water-Module Interaction Research

It is recognized that water, besides accelerating corrosion reactions within PV modules, catalyzes a host of other degradative phenomena such as delaminations, reduction of mechanical strength, enhancement of electrical breakdown probability, etc. The purpose of this research is to understand these interactions and to develop means to deal with them.

A fundamental study in this area is the measurement of water sorption by PV encapsulants. Sorption data are obtained using a Cahn Balance mounted above an environmental chamber within which the encapsulant specimen, suspended from one arm of the balance, is exposed to a controlled T/RH environment.

To address the question of how exposure to UV affects encapsulant sorption properties, Chronar-supplied substrate films mounted on Pyrex glass slides have been weighed. The sorption isotherms of some of these pristine samples will be determined with the Cahn Balance. The remaining samples have been mounted in the Bemco chamber for exposure at 85°C/10% RH to 1 UV sun. After a suitable period, the sorption isotherms of these UV-exposed samples will be obtained and the effect of photothermal exposure on EVA sorption characteristics determined.

Liquid water also contributes to module degradation. To ascertain the effects of the transition from a cool night to a warm day (dew formation), a specially prepared PVB sample was mounted to a heat exchanger that allowed sample heating and cooling independently of the controlled Bemco chamber ambient conditions. The sample was exposed to simulated day-night cycles so as to induce the formation of dew during the "night." With the onset of "day," large current transients were observed (specifically, for the surface current) that decayed to steady values as the "day" progressed. These large current spikes were not evident when there was no dew.

A hermetically sealed module should respond only to thermal, not humidity, changes in the environment. To test this supposition, a PVB sample was conditioned for 24 h in a vacuum at 40°C, then sealed and exposed to various humidity levels at both 40 and 85°C. Bulk and surface currents were observed to remain relatively steady. Leakage current response obeyed the usual Arrhenius temperature law.

Mini-modules mounted at the JPL outdoor test stand were observed to exhibit large current spikes during the transition from dewy dawn to warmer morning. Leakage current response of SVI samples, discussed above, and XTEST samples (encapsulated cell-frame module-like test coupons originally used to determine module electrochemical corrosion mechanisms and rates) were characterized in controlled steady laboratory environments. It was then decided to mount these samples in an outdoor environment and so characterize their response in a transient environment.

An ongoing analytical study of the experimental data parallels the experimental effort. Mathematical models of module behavior are continually being formulated and modified in accordance with the measurement data. In turn, the analysis provides direction for future experimentation.

2. Photothermal Stability Research

A model of autocatalytic photooxidation has been proposed. Photooxidation initially takes place at a slow rate while generating degraded products. These products will, in turn, catalyze further photooxidation reactions resulting in a drastic increase in the rate of subsequent degradation.

EVA samples have been aged at 120 and 135°C with varying UV intensities. Optical transmission changes were analyzed. The rate of loss of transmission which can be correlated to the formation of photooxidation products was monitored. These rates can be compared with those obtained during the initial stage of aging to validate the autocatalytic photooxidation model.

A program to study the failure of Tedlar/EVA/stainless steel modules was initiated. Cracking, observed outdoors in real time conditions, was simulated in accelerated testing. An experimental technique was developed to quantitatively assess the extent of degradation. Photothermal aging was carried out of freestanding Tedlar films at 6 suns, 85°C for up to 23 days. Stress-strain measurement of these samples showed no significant change in mechanical properties. This is in contrast to module testing results in which Tedlar film in a Tedlar/EVA encapsulated module showed signs of embrittlement after 21 days of photothermal aging at six suns and 85°C. Potential synergistic effects of Tedlar and EVA are being investigated.

A report has been published by E. Cuddihy, entitled The Aging Correlation (RH + t): Relative Humidity (%) + Temperature (°C), JPL Publication 86-7, 5101-283, DOE/JPL-1012-121, dated January 15, 1986. This report discusses an aging correlation between corrosion lifetime and relative humidity RH (%) and temperature t (°C) in relation to activities supported by the FSA Project to better understand the fundamental mechanisms of degradation and aging.

University of Toronto researchers are continuing their work on computer modeling of photooxidation of polymers. They have modified their previously developed computer program for the simulation of the photooxidation and photostabilization of hydrocarbons to ANSI standard FORTRAN and a new interactive version has been developed. They also have included in the night-day cycles of their file-oriented simulation program the possibility of varying temperature during such cycles. This modification has greatly increased the accuracy in predicting what the actual time to failure (time required to break 5% of C-H bonds) in polyethylene and EVA.

### 3. Reliability-Durability of Bonding Materials

A comprehensive effort on chemical bonding has been completed with issuance of JPL Publication 866, 5101-284, DOE/JPL-1012-120, Chemical Bonding Technology: Direct Investigation of Interfacial Bonds, by J.L. Koenig, et al., dated January 1986.

Dr. Plueddemann of Dow Corning had previously developed a successful primer for bonding EVA to glass that carries the Springborn designation A-11861. This primer, based on organosilane chemistry, has achieved enormous industrial acceptance. Experimental testing has found that this primer acts to significantly reduce the quantities of water absorbed at the interface between glass and EVA, an important factor related to limiting module leakage current. Dr. Plueddemann therefore continues the development of experimental organosilane coupling agents that are even more highly hydrophobic, with the intent to further reduce the quantities of interfacially absorbed water. In turn, this would lead to improved resistance to electrical-leakage currents.

An experimental prototype of a more hydrophobic coupling agent (primer) has been completed at Dow Corning, and the designation of this experimental primer is X1-6121. Sample quantities have been sent to JPL and Springborn. JPL will measure leakage current, whereas Springborn will prepare test specimens of glass beads dispersed in EVA, with and without the new Dow Corning primer X1-6121. When prepared, the equilibrium absorbed water contents will be measured and compared with samples using the standard 11861 EVA/glass primer. This test is to determine if the new primer indeed acts to further reduce the absorption of interfacial water by PV modules.

The finding that organosilane coupling agents act to reduce interfacial water has significance for corrosion protection. Metallic corrosion usually requires the presence of liquid water, as one necessary requirement. The adhesion studies with primed EVA/glass specimens clearly demonstrated that organosilane coupling agents are enormously effective in reducing the accumulation of interfacial water. This suggests that organosilanes chemically reacted onto metallic surfaces may function as anti-corrosion agents, through the action of reducing or excluding liquid water at the metallic surface. Dr. J. Boerio, University of Cincinnati, is carrying out the studies to determine if organosilane coupling agents can function as anti-corrosion agents for the aluminum metallization employed on crystalline-silicon solar cells.

Dr. Boerio has experimentally been able to chemically monitor the interface between EVA and an aluminized back surface of solar cells. The successful technique is based on reflectance IR spectroscopy. In initial experiments, Boerio has successfully monitored aluminum corrosion when using unprimed samples of EVA on the solar cell back surface. Next, the aluminized back surface of the same commercial solar cell was primed with A-11861 primer, followed by overcoating with a laminated and cured layer of EVA. This work is in progress, but initial results show that no corrosion has formed after 1 week of immersion in boiling water. The aging is continuing, but already the evidence is accumulating that a self-priming EVA with A-11861 coupling agent accomplishes both structural bonding to glass, and also corrosion protection for the solar cell's aluminized back surface. There is great industrial interest in a self-priming EVA for these two functions.

### 4. Reliability-Durability of Electrical Insulation

A theory, developed at JPL, suggests that the fundamentally correct definition of the intrinsic dielectric strength property of electrical insulation material has been identified. This new theory has been published as a project report by E. Cuddihy, A Concept for the Intrinsic Dielectric Strength of Electrical Insulation Materials, JPL Publication 85-20, 5105-252, DOE/JPL-1012-105, dated April 15, 1985. It also has been submitted for formal publication in the Journal, IEEE Transactions on Electrical Insulation.

Based on these theories, an experimental capability to measure the intrinsic DC dielectric strength property has been established at Springborn Laboratories, and can now be monitored as a function of aging. For this purpose, the DC dielectric strength of A-9918 EVA is being monitored as a function of aging on the outdoor photothermal aging racks (OPTAR), which are being operated at 70, 90, and 105°C. The EVA is also being aged in UV-accelerated RS/4 chambers at 50°C and at 85°C. There are two RS/4 chambers being operated at 50°C, one with and one without a periodic water spray cycle. These are referred to as RS/4-dry and RS/4-wet. The unit operating at 85°C is dry. DC dielectric strength values have been measured at 2000 and 4000 h of aging in the RS/4 chambers, and at 2000 h on the outdoor racks. These data are summarized in Table 1.

The trend indicates a reduction in the DC dielectric strength with dry aging in the RS/4 chambers, and also outdoors on the heating racks. Wet RS/4 aging at 50°C, however, results in an increase in the DC dielectric strength. The speculation is that aging causes an increase in ionic species in the EVA which could reduce the DC dielectric strength, whereas the water spray cycle results in extraction of these ionic species. Thus, the DC dielectric strength increases for wet aging while it decreases for dry aging, or under conditions where ionic extraction does not occur. These aging experiments are continuing.

JPL has developed specialized test equipment that permits the direct, non-destructive, in situ measurement of selected electrical properties of

Table 1. DC Dielectric Strength, Volts/mil

| | Aging Time, Hours | | |
|---|---|---|---|
| Sample | 0 | 2000 | 4000 |
| RS/4-Dry, 50°C | 3500 | 3060 | 3240 |
| RS/4-Dry, 85°C | 3500 | 2100 | 1980 |
| RS/4-Wet, 50°C | 3500 | 3830 | 4120 |
| OPTAR 70°C | 3500 | 2850 | -- |
| OPTAR 90°C | 3500 | 3140 | -- |
| OPTAR 105°C | 3500 | * | -- |

*Sample untestable.

materials undergoing accelerated aging in environmental aging chambers. These measurements can be made on scheduled intervals without the need to remove the aging samples from the chambers. This equipment will enable automatic in situ measurement of partial discharge, the pulse height analysis measurements of specimens undergoing temperature/humidity exposure, and electrochemical leakage current. JPL also operates a Biddle high-voltage tester to measure the voltage breakdown characteristics of control and aged test specimens. This latter test is destructive in nature.

In preparation for electrical aging experiments at JPL, Chronar supplied six self-adhesive films which have been applied to aluminum substrate plates. Four samples each, of these polymer films, were prepared at JPL. One of the four samples of each type was used as a control, to first measure its set of non-destructive electrical properties, followed by the destructive measurement of its voltage breakdown level. Two of the remaining three samples of each type were placed in the environmental aging chamber in which a constant temperature/humidity/UV environment is being maintained. The remaining sample is being exposed outdoors at the JPL test facility.

Non-destructive measurements of corona inception voltage and pulse height analysis have been made on Chronar self-adhesive films mounted on aluminum substrates. This set of measurements were made after approximately 500 h of exposure to 1 UV sun and a chamber environment of 85°C/5% RH. Comparisons will be made with the original measurements on the control samples, and aging will be continued. These data will ultimately be analyzed to ascertain the effects of aging on parameters that assess propensity for an insulation to break down electrically. Similar data on the samples exposed to an outdoor environment at the JPL test stand will be obtained at the end of summer.

5. Module Flammability Research

The research effort to develop the technology base required to construct fire-ratable PV modules using hydrocarbon encapsulants has resulted in the identification of several high-temperature, back-surface candidate materials capable of raising the fire resistance of modules to Class A and Class B levels.

During this reporting period, another series of Class A burning-brand tests was completed in October 1985. The focus of this test series was to evaluate several edge-seal systems and perform array-level flammability tests. The results indicated that very few edge-seal systems were able to pass the test with a Class A burning brand placed over the module's aluminum frame. In most of these cases, success was attributed to edge materials that were not consumed by the intense heat. Post-test analyses indicated that failure was caused by one of two mechanisms: complete loss of the edge material, or loss of edge-material structural properties because of heat. Both of these failures, resulting in loosening and separation of the back-surface material and glass from the aluminum channel, eventually led to flame penetration at or near the aluminum channel.

Array-level tests were conducted using two modules mounted above a UL standard Class A burning-brand-test deck to simulate a typical roof section. Although test results varied, the key factor was maintaining module back-surface integrity, at least to the extent that the roofing felt was not ignited. In these cases, the amount of damage to the roofing felt was minimal. The installation of fire-rated shingles, shakes, or rolled roofing (which for these tests was not used) would provide an additional margin of safety. Thus, special high-temperature edge-seal systems may only be necessary for integral-mount applications.

Dielectric and voltage breakdown tests were performed to understand why modules using HITCO 7628 have not been able to pass the JPL Block V high-pot test. Test results on both Solarex Corp. and ARCO Solar, Inc. modules indicated that the HITCO material may have a low dielectric withstand capability relative to other materials, such as Tedlar. Tests on samples of the HITCO 7628 material not integrated into a module verify results obtained at the module level. Leakage current in excess of 50 μA occurs through the material below the minimum acceptance 1500 V level.

Samples of the HITCO 7628 material (coated on two sides) were bound to Kapton and to a TPX methylpentene polymer. Results of dielectric and voltage breakdown testing at the material level indicate that using either of these materials with the high-temperature, HITCO material is sufficient to provide voltage withstand in excess of JPL Block V requirements. At present, samples of Kapton and TPX methylpentene polymer, laminated to HITCO 7628, have been subjected to a chamber environment of 85C for 7 days and 85C/85% RH for 45 days. Inspection after the 52-day period of the Kapton samples showed no visible signs of delamination, while the TPX samples showed a slight curling. The samples were returned to the chamber and will be subjected to further high-pot testing in June.

6. Crystalline-Silicon Module Development

The long sought goal of demonstrating 15% PV module efficiency has been realized. On the JPL High-Efficiency Module Contract with Spire Corp., Spire has delivered a module that JPL measurements show to have 15.2% efficiency at standard conditions [100 mW per sq cm irradiance, ASTM 892-82 (global) irradiance spectrum and 25°C cell temperature]. Encapsulated cell efficiency is 16.9%.

The module power output is 75.2 W. Dimensions are 91.2 x 54.2 cm and the packing factor is 0.901. The module contains 84 cells, each 53.0 sq cm in area. The cells are manufactured from float-zone-grown silicon ingot. Spire has produced similar cells manufactured from Cz-grown silicon ingot, indicating that the 15% goal is achievable with the more readily available Cz material.

The practicality of repeatable production of high-efficiency module cells was demonstrated during the manufacture of cells for the above module. For one batch of 25 cells, the yield was 100% and the average cell efficiency was 18.1%.

The cell design for the high-efficiency module was selected after a variety of designs had been manufactured and incorporated into mini-modules to measure module efficiency and normal operating cell temperature (NOCT). One type of cell, incorporating a BSR and a polished front surface, was shown to result in a module NOCT 4°C less (46°C) than was the case for cells without the BSR and with texture etched front surfaces. It had been hoped that the BSR approach would provide the higher efficiency (of the two approaches) at NOCT. Experiments indicated, however, that the efficiency of the latter cells could be made higher enough at any given temperature as to surpass the performance of the BSR cells at NOCT. The texture etched cells, therefore, were selected as the preferred design.

An advantage of the BSR approach is the expected longer life of the cells because of lower NOCT. It did not seem useful to investigate the economic trade-off because it was not possible to carry on the effort long enough to optimize both cell designs and obtain a reliable measure of the difference in their efficiencies.

7. Module Environmental Testing

The last program of Block V tests has been completed on commercial crystalline-silicon modules, involving module manufacturers from France, Italy, the United States, West Germany, and Japan. The only other tests performed were on a-Si modules. The results of environmental testing performed during the reporting period are shown in Table 2.

Table 2. Block V Tests of Commercial Crystalline-Silicon Modules

| Module Code | Quantity | Test | Results |
|---|---|---|---|
| D4 | 1 | Hot spot | Some discoloration of interconnects and collectors. Two small cell cracks |
| J1 | 4 | MI-10K | Cell string resistance increased for all modules for up, neutral plane, and downward forces. Unacceptable power loss of -11, -13, -15, and -36%, respectively |
| | 6 | Final hi-pot/ continuity | Satisfactory |
| | 1 | Hot spot | Satisfactory |
| E2 | 2 | T150 | Discoloration of gridlines adjacent to frame |
| | 6 | Final hi-pot/ continuity | Satisfactory |
| | 1 | Hot spot | Blistering of cells, burning of Tedlar |
| V2 | 4 | T-50 | One o.k., three electrical failures at -7, -7, and -23% |
| | 2 | HF-10 | J-boxes yellowing |
| | 1 | T-150 | J-box yellowing |
| | 2 | MI-10K | Three cracked cells, power satisfactory |
| | 3 | Final hi-pot/ continuity | One failed hi-pot, continuity satisfactory |
| | 1 | Hot spot | Satisfactory |
| V3 | 4 | T-50 | Satisfactory |
| | 3 | HF-10 | J-boxes yellowing, some cell discoloration |
| | 1 | T-150 | Satisfactory |

Table 2. (Cont'd)

| Module Code | Quantity | Test | Results |
|---|---|---|---|
| | 3 | MI-10K | Satisfactory |
| | 4 | Final hi-pot/ continuity | Satisfactory |
| | 1 | Hot spot | Satisfactory |
| V4 | 4 | T-50 | Satisfactory |
| | 3 | HF-10 | J-boxes yellowing |
| | 1 | T-150 | J-box yellowing |
| | 3 | MI-10K | Satisfactory |
| | 4 | Final hi-pot/ continuity | Satisfactory |
| V5 | 4 | T-50 | Satisfactory |
| | 3 | HF-10 | J-boxes yellowing |
| | 1 | T-150 | J-box yellowing |
| | 3 | MI-10K | Satisfactory |
| | 4 | Final hi-pot/ continuity | Satisfactory |
| 01 | 4 | HF-10 | Minor warping of J-boxes |
| | 4 | MI-10K | Satisfactory |
| | 2 | T-150 | Satisfactory |
| | 4 | MI-10K | Satisfactory |
| | 7 | Final hi-pot/ continuity | Satisfactory |
| | 1 | HS-100 | Two of the tested cells have one blister each, burned encapsulant surrounding one interconnect |

Table 2. (Cont'd)

| Module Code | Quantity | Test | Results |
|---|---|---|---|
| KA a-Si | 2 | HF-10 | Electrical failures, major delamination back surface, one module |
| KP a-Si | 2 | HF-10 | Electrical failures, increased delamination of cover glass and encapsulant |
| | 1 | T-150 | Electrical failure, additional delamination of module glass and cover glass, tearing of Tedlar around J-box |
| | 2 | HF-10 | Electrical failures, additional delamination of module glass and cover glass |
| OH | 10 | Hi-pot continuity | Six modules failed initial continuity test, in some cases at very high resistance |
| | 6 | T-50 | Some cover glass delamination, Tedlar delaminating adjacent to frame edge |
| | 2 | T-150 | One cracked cell, additional delamination of cover glass and Tedlar |
| | 4 | HF-10 | Satisfactory |
| | 4 | MI-10K | Satisfactory |
| | 6 | Final hi-pot/ continuity | Satisfactory |
| | 1 | Hot spot | Satisfactory |
| UF | 6 | Hi-pot | Failed |
| | 6 | continuity | Satisfactory |
| UM | 4 | Hi-pot/ continuity | Satisfactory |
| W2 | 1 | Hot spot | Satisfactory |

Table 2. (Cont'd)

| Module Code | Quantity | Test | Results |
|---|---|---|---|
| R3 | 1 | Hot spot | Satisfactory |
| SO a-Si | 1 | Hail | Power satisfactory, module surface dimpled |
| Y a-Si | 2 | Hail | Power satisfactory, glass cracked in one module, probably because of a distorted frame |

T-50 = 50 thermal cycles, [illegible] to +90°C.

T-150 = 200 thermal cycles (150 plus original 50).

HF-10 = 10 humidity/freeze cycles. 85°C/85% RH, then -40°C, 10 cycles (days).

MI-10K = Mechanical cycling, 50 lb/ft squared (2400 Pa) alternating, 10,000 cycles.

Continuity = Electric current at twice the Isc across joints in the metal frame for 2 min. Allowable voltage drop, 1 V.

8. Electrical Measurements Technology Development

Following the calibration of 18 reference cells at JPL and SERI as part of the Commission of European Communities (CEC) Round-Robin of measurements on reference cells, the data were sent to the CEC Joint Research Center (JRC), Ispra, Italy, on August 5, 1985. During September 9-11, 1985, M. Smokler and R. Mueller attended the Second Expert Meeting on the Collaborative Project on Solar Energy in Ispra, Italy, as the U.S. participants. This project is directed by the Summit Working Group on Technology, Growth, and Employment, and the operating agent is the CEC JRC in Ispra.

The meeting was held to discuss the results and methods of the participants in the CEC Round-Robin of measurements on reference cells. The other participating countries were the United Kingdom, France, Italy, West Germany, and Japan. Considerable interest was expressed in the JPL results obtained with the filtered LAPSS (a JPL development). The characteristics of this device were incorporated into the recommendations made by the meeting participants. The filtered LAPSS provided accurate measurements using a relatively unsophisticated method. The Round-Robin was considered to be successful in achieving its objectives. In spite of the wide variety of methods and equipment used by the participants, a first comparison of the results showed agreement to within ±2% for crystalline-silicon cells and ±2.5% for a-Si cells among the majority of the participants (JPL and SERI included).

R. Mueller attended two regular and two interim meetings of the ASTM E44.09 subcommittee on Photovoltaic Electric Power Systems and authored the subcommittee draft Document 130, "Standard Method for the Calibration of Non-concentrator Terrestrial Photovoltaic Primary Reference Cells Under Direct Irradiance." This document has been approved by subcommittee ballot and will soon be presented for a full E44 committee ballot. He also has been shepherding a proposed draft on a Standard Method for Measuring the NOCT of a PV Module. It has been well received, but it has been decided that the method must first be tried and proven at two or three more laboratories other than JPL before it could be accepted as a proposed ASTM draft document.

The British Petroleum (BP) Round-Robin of measurements on modules was completed in Europe during late 1985. The results were made available to JPL and there was concern about the JPL measurements apparently being too low. It was learned that JPL and the Europeans (BP and Ispra) were not using the same Reference Spectral Irradiance Distributions (RSID) when correcting the solar simulator measurements. When the module and reference cell measurements taken at JPL were corrected to the same RSIDs as were those taken by Ispra, the average difference is less than 1% for the reference cell calibrations and ±2% for the module power measurements. The comparison between JPL and BP reference cell calibrations remains not very good. The average difference remains at 2% with a high standard deviation of nearly 4%. These results were submitted to BP.

A paper, titled Air Mass 1.5 Global and Direct Solar Simulation and Secondary Reference Cell Calibration Using a Filtered Large Area Pulsed Solar Simulator, was presented at the 18th IEEE Photovoltaics Specialists Conference in Las Vegas, Nevada, on October 25, 1985.

Many measurements were made using the JPL filtered LAPSS to assist numerous vendors with the accuracy of their measurements. During this reporting period, the most significant support was that of performing electrical measurements on the Spire high-efficiency cells, mini-modules, and modules as they made improvements and finally achieved a module efficiency of over 15% when measured using the JPL global filtered LAPSS. Temperature coefficient measurements were also made on several types of a-Si modules. Testing the a-Si modules led to the discovery that it was necessary to make changes in the LAPSS program software to accommodate these devices. The testing procedure had to be changed, including eventual hardware modifications, to avoid stressing or damaging these devices because of voltages presented by the LAPSS data acquisition system during testing. It also was determined through computer analysis of the LAPSS global spectral irradiance distribution that it is a close match to the Air Mass Zero spectral irradiance distribution.

9. Module Failure Analysis

A Solar Power Corp. module (Model G12-361CT, S/N 13197) reported intermittent loss in $V_{OC}$. This module consists of 36 crystalline cells in series. This intermittent failure was not verified. Metallic contamination and dendrite growth, however, was found on the insulating material between the contact pads on the terminal printed circuit (PC) board. This contamination is suggested as the cause for the reported failure.

A polysilicon module, VB2H-3013 (from Photowatt), was received at the failure analysis (FA) lab on August 27 with a reported 23% power loss after a T-50 test. The reported 23% power loss was found to be caused by four cracked cells. This is one of the four modules encapsulated with PVB/Tedlar system. No other encapsulant systems such as EVA/Tedlar, EVA/glass, or PVB/glass have failed in T-50. This failed module consists of 36 cells in series, with two shunt diodes for each 18-cell string. Laser scanning by the 5145Å Argon laser showed one broken cell, and laser scanning by the 6328Å He-Ne laser showed four broken cells at the first scan, indicating the current limited by the broken cell.

The second scan with the same He-Ne laser, however, showed two broken cells, indicating an intermittent problem of the two cells. The cracks on these cells intermittently isolated portions of the cell topside from the remainder of the cell string. When three of these cells were shorted across, module power increased to just 10% below the power of the module when it was received. The mechanism responsible for cracking the cells is not well understood. Three more PVB/Tedlar modules have been received at the Failure Analysis Lab. (S/N VB2H-3014 and S/N VB2H-3015 both underwent T-50, HF-10, and M/I testing and showed power losses of 7.0 and 1.6%, respectively. S/N VB2H-2955 underwent T-200 and showed a power loss of 10.4%).

The laser scanner showed some cell cracking in all of these modules. Additional Photowatt modules that incorporate encapsulation systems other than PVB/Tedlar have been received at the FA lab. These include two modules each of PVB/glass, EVA/Tedlar, and EVA/glass. All of the modules have a test history similar to that for the PVB/Tedlar modules, but show every little degradation (<2.4%) in their electrical power. No cracking was observed when the PVB/glass, EVA/Tedlar, and EVA/glass modules were examined visually. Laser scanning of the modules did not show any cell racking. The top side cover glass of the PVB/Tedlar and EVA/Tedlar modules was found to have a rough texture, whereas the top side cover glasses of the PVB/glass and EVA/glass modules were found to be smooth. The Tedlar back side of the PVB/Tedlar modules were found to wrinkle after environmental testing, but the Tedlar back side of the EVA/Tedlar modules was found to remain smooth after environmental testing. This suggests that the cause for cell cracking in the PVB/Tedlar module is related to thermal expansion of the PVB encapsulant.

Analysis of the polycrystalline silicon module from Siemens (BJOH-2558) has been completed. A 34% power loss after 10 K cycles mechanical integrity test was reported. This module consists of 144 4-in. diameter circular cells: four in parallel, and 36 in series. Four shunt diodes were externally installed, each in parallel with four 9-cell strings. The solar cell laser scanner indicates that one of the four 9-cell strings does not contribute any power to the output. Close examination of the I-V characteristics of the individual strings indicates that most of the output power of half of the module is generated by three strings out of eight. Dark I-V characteristics of the two submodules, each consisting of four parallel strings, did not show any clear differences between strings. Photocurrent images of the module were reexamined by a solar-cell laser scanner, using an argon laser with and without the shunt diodes. No clear differences between strings were observed for the images even at the highest laser-power level of the equipment. Intermittent characteristics of the module in the SCLS and light I-V curves were verified as being caused by a stress-sensitive discontinuity of the cell interconnects.


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# PROCEEDINGS OF THE 26th PROJECT INTEGRATION MEETING

# PROCEEDINGS

INTRODUCTION

The 26th and final Project Integration Meeting (PIM) of the Flat-Plate Solar Array (FSA) Project of the Jet Propulsion Laboratory was held at the Pasadena Center, Pasadena, California, on April 29 and 30, and May 1, 1986.

The thrust of this meeting was to summarize the Project's non-concentrating, crystalline-silicon, solar-cell research and development (R&D) activities of the past 11 years. This R&D has provided the majority of the technology base for today's crystalline-silicon, terrestrial photovoltaic module production, and has established a foundation of technology for tomorrow's higher-efficiency, lower-cost, and more reliable modules.

The meeting was divided into three specific areas of interest with each day devoted to one of these areas:

Day 1 (April 29) consisted of an overview of the progress and the significance of the results of the 11 years of Project activities, and a discussion of future needs and directions.

Day 2 (April 30) provided detailed technical summaries of the progress of FSA contractors and in-house work since the 25th PIM (June 19-20, 1985).

Day 3 (May 1, morning) provided an opportunity for industry and users to explain their continuing participation in the manufacture and use of crystalline-silicon photovoltaics.

A summary of each of these days is presented later in this document.

A final set of Project documentation is currently being prepared and will be distributed late this year, and will be available through the National Technical Information Service.

As this was the last PIM, and because this will be the final PIM Proceeding and Progress Report, the FSA Project would like to take this opportunity to thank all of the organizations and individuals who have participated in the Project during the last 11 years. It has been your continued dedication and contributions that have made the Project the success that it is. We salute you and wish you continued success in the future.

26th FLAT-PLATE SOLAR ARRAY (FSA)

PROJECT INTEGRATION MEETING (PIM)

AGENDA

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April 29 (Tuesday)

7:30 a.m. Registration (Lobby)

ONE-DAY OVERVIEW (Room C124)

| | | | |
|---|---|---|---|
| 8:30 | Welcome and Announcements | W. Callaghan (JPL) | 15 min |
| | DOE comments | M. Prince (DOE) | 15 min |
| | Historical Overview, Accomplishments, and Value of the FSA Project | | 60 min |
| | Government | P. Maycock (PV Energy Systems) | |
| | Industry | R. Little (Spire Corp.) | |
| 10:00 | BREAK AND PARALLEL DOE MEETING | | 40 min |
| | A short (25 min) DOE briefing for the press and invitees who have never attended a PIM. DOE will give a brief overview of their National PV Program and introduce the key personnel from DOE, JPL, Sandia, and SERI. A question and answer period will follow. | | |
| 10:40 | Crystalline-Silicon PV Summaries: Accomplishments, Lessons Learned, Potential and Continuing R&D Needs | | |
| | Silicon Material | J. Lorenz (Consultant) | 20 min |
| | Silicon Sheet | F. Wald (Mobil Solar Energy Corp.) | 25 min |
| | Higher-Efficiency Cell Research | A. Rohatgi (Georgia Tech.) | 20 min |
| | Processing R&D | D. Bickler (JPL) | 20 min |
| 12:05 | LUNCH | | |
| 1:20 | Summaries: Continuation | | |
| | Encapsulation | P. Willis (Springborn Labs, Inc.) | 20 min |
| | Module Design and Reliability | R. Ross (JPL) | 25 min |
| | Module Evaluation | C. Gay (ARCO Solar, Inc.) | 20 min |
| | Economic Analyses | H. Macomber (Consultant) | 20 min |
| 2:45 | BREAK | | |
| 3:15 | Panel: R. Annan, Chairman (DOE) | | 2 hours |
| | Recommendations for Crystalline-Silicon in DOE's 5-Year Photovoltaic Research Plan | J. Day (Strategies Unlimited)<br>G. Smith (Naval Weapons Center)<br>K. Firor (PG&E)<br>G. Ralph (Hughes Aircraft)<br>K. Koliwad (JPL)<br>C. Rose (Westinghouse)<br>R. Daniels (Solarex) | |
| 5:15 | Closing Remarks: FSA and DOE | | 20 min |
| 5:35 | Social Hour | | |

April 30 THREE PARALLEL TECHNICAL SESSIONS (see next page).

May 1 INDUSTRY-USERS DAY (morning), agenda to be announced.

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CELL TECHNOLOGY AGENDA

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April 30 (Wednesday) (Room C124)

ADVANCED SILICON SHEET

A. Morrison, Chairman

| | | | |
|---|---|---|---|
| 8:00 | Fourth Silicon Stress/Strain Workshop | M. Leipold (JPL) | 10 min |
| 8:10 | Dendritic Web Ribbon | R. Hopkins (Westinghouse Electric Corp.) | 35 min |
| 8:45 | JPL Web Team | D. Bickler (JPL) | 20 min |
| 9:05 | Stress and Efficiency Studies in Edge-Defined Film-Fed Growth of Silicon Ribbons | J. Kalejs (Mobil Solar Energy Corp.) | 20 min |
| 9:25 | Optimization of Silicon Crystals for High-Efficiency Solar Cells | T. Cizek (Solar Energy Research Institute) | 20 min |
| 9:45 | BREAK | | |
| 10:05 | Analysis of Stress/Strain Relationships in Sheet | O. Dillon (Univ. of Kentucky) | 20 min |
| 10:25 | Sheet Stress/Strain Activities at JPL | B. Wada (JPL) | 10 min |
| 10:35 | High-Temperature Testing of Silicon | T. O'Donnell (JPL) | 10 min |
| 10:45 | Characterization of Silicon Sheet | S. Hyland (Cornell Univ.) | 20 min |
| 11:05 | Silicon Sheet Surface Studies | S. Danyluk (Univ. of Illinois at Chicago) | 20 min |
| 11:25 | Czochralski Crystal Growth Modeling Study | M. Dudukovic (Washington Univ., St. Louis) | 20 min |
| 11:45 | LUNCH | | 75 min |

HIGH-EFFICIENCY SOLAR CELLS

P. Alexander, Chairman

| | | | |
|---|---|---|---|
| 1:00 | Optimization Methods and Solar Cell Numerical Models | S. Jacobsen (Univ. of California, L.A.) | 15 min |
| 1:15 | Novel Measurement Techniques | M. Wolf (Univ. of Pennsylvania) | 10 min |
| 1:25 | Measurement of Lifetime and Diffusion Length in Heavily Doped p-Type Silicon | R. Swanson (Stanford Univ.) | 20 min |
| 1:45 | Surface Passivation ($SiN_x$) | L. Olsen (Univ. of Washington) | 20 min |
| 2:05 | High-Efficiency Solar Cells on Web | D. Meier (Westinghouse Electric Corp.) | 20 min |

PROCESSING

B. Gallagher, Chairman

| | | | |
|---|---|---|---|
| 2:25 | Diffusion Barriers | E. Kolawa (California Inst. of Technology) | 20 min |
| 2:45 | BREAK | | |
| 3:05 | MOD Film Development | J. Parker (Electrink) | 10 min |
| 3:15 | Ink-Jet Printer System | R. Vest (Purdue Univ.) | 20 min |
| 3:35 | Laser-Assisted Cell Metallization | D. Meier (Westinghouse Electric Corp.) | 20 min |
| 3:55 | Simultaneous Junction Formation Using Liquid Dopants | R. Campbell (Westinghouse Electric Corp.) | 15 min |
| 4:10 | Rapid Thermal Processing (RTP) of Ion-Implanted Silicon | G. Rozgonyi (North Carolina State Univ.) | 20 min |
| 4:30 | Hydrogen Ion Implantation | S. Fonash (Pennsylvania State Univ.) | 20 min |
| 4:50 | Low-Pressure CVD of Polysilicon | B. Gallagher (JPL) | 10 min |

## MODULE AND RELIABILITY TECHNOLOGY AGENDA

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April 30 (Wednesday) (Room C101-102)

### MODULE TECHNOLOGY

M. Smokler, Chairman

| | | | |
|---|---|---|---|
| 8:00 | Accuracy and Long-Term Stability of Amorphous-Silicon Measurements | R. Mueller (JPL) | 20 min |
| 8:20 | Long-Term Stability of Amorphous-Silicon Modules | R. Ross (JPL) | 30 min |
| 8:50 | Reliability Testing of Thin-Film Cells | J. Lathrop (Clemson Univ.) | 30 min |
| 9:20 | Long-Term Module Testing at Wyle Laboratory | D. Otth (JPL) | 20 min |
| 9:40 | BREAK | | |
| 10:00 | Module Encapsulation Technology | P. Willis (Springborn Laboratory) | 30 min |
| 10:30 | Commercial Module Test Program | M. Smokler (JPL) | 20 min |
| 10:50 | High-Efficiency Module Development | M. Spitzer (Spire Corp.) | 20 min |
| 11:10 | Measuring Research Progress in Photovoltaics | B. Jackson (JPL) | 30 min |
| 11:40 | LUNCH | | |

### RELIABILITY PHYSICS

E. Cuddihy, Chairman

| | | | |
|---|---|---|---|
| 1:00 | Mechanistic Studies of Photothermal Aging | R. Liang (JPL) | 20 min |
| 1:20 | UV-T-RH Combined Environmental Testing | C. Gonzalez (JPL) | 20 min |
| 1:40 | Computer Modeling of Photodegradation | J. Guillet (Univ. of Toronto) | 20 min |
| 2:00 | Chemical Bonding Technology | E. Plueddemann (Dow Corning) | 15 min |
| 2:15 | Anticorrosion Studies | J. Boerio (Univ. of Cincinnati) | 15 min |
| 2:30 | BREAK | | |
| 2:50 | Electrochemical Aging Effects in Modules | G. Mon (JPL) | 30 min |
| 3:20 | Leakage-Current Properties of Encapsulants | A. Wen (JPL) | 30 min |
| 3:50 | Water Permeation and Dielectric Properties | J. Orehotsky (Wilkes College) | 30 min |

## SILICON MATERIALS

R. Lutwack, Chairman

April 30 (Wednesday) (Room C103)

| | | | |
|---|---|---|---|
| 1:00 | Workshop Summary: Low-Cost Polysilicon for Terrestrial PV Solar Cell Applications | R. Lutwack (JPL) | 20 min |
| 1:20 | Silane Process Research and Development | S. Iya (Union Carbide Corp.) | 20 min |

# Plenary Sessions

SUMMARY

After welcoming participants to the 26th and final Project Integration Meeting (PIM), W.T. Callaghan, Manager of the Flat-Plate Solar Array (FSA) Project at the Jet Propulsion Laboratory (JPL), announced that, as requested by the U.S. Department of Energy (DOE), JPL plans to phase out FSA as of the end of September 1986. After that, in place of FSA, JPL will support the DOE National Photovoltaic Program in specific photovoltaic (PV) activities.

Since the FSA Project began in 1975, prices of PV modules have been reduced by a factor of 15, module efficiencies have increased by a factor of 3, and 10-year warranties now are available where there were none before. On the other hand, significant challenges face U.S. PV companies as foreign PV programs have increased and public interest has decreased because of reduced fossil-fuel energy prices and lessened interest in long-term energy planning.

Callaghan announced and displayed a long-term goal of the FSA Project: a 15.2%, AM 1.5, 75.2 W module (STC, global spectra). The module, developed by Spire Corp. under contract to FSA, represents the first, full-sized, 15% efficient, flat-plate, crystalline-silicon PV module ever made.

Morton Prince, who has been in the DOE National Photovoltaic Program Office throughout the life of the FSA Project, stated, "Many of the original objectives of the FSA Project have been accomplished and several objectives are close to meeting their goals. All of this was accomplished with less than 36% of the original budget, even without taking inflation into account. Part of this accomplishment is due to you in industry as you have been willing (rightfully so) to cost-share many of the more expensive items and I want to thank you for your contributions to our success."

Prince listed some key technology parameters for single-crystal silicon technology along with his beliefs as to what the status of these parameters was, is, and will be. Improvements still are possible with silicon, however, such as improved efficiencies and improved understanding of ribbon technology. He stated that DOE believes that these improvements are still worth pursuing and hopes to have JPL and others make these improvements.

Paul Maycock, Photovoltaic Energy Systems, Inc., presented an historical overview of the initiation and early events of national PV activities, including those of FSA. His viewpoints on major conclusions and results of the JPL/FSA activities are as follows:

Because of the DOE/JPL program, more than 2000 professionals devoted their careers to solving cost and performance problems in photovoltaics.

Virtually all of th echnical feasibility and technical readiness goals were fully met by the JPL/DOE effort.

The shift in emphasis in 1981 from a balanced, well funded, research development test and evaluation PV program to an underfunded, high-risk research effort delayed the carefully planned transition from technology

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readiness to commercial readiness. JPL was forced to cancel five key commercial readiness contracts involving silicon production, sheet production, ingot casting, and crystal film deposition.

Crystal-silicon photovoltaics is a truly remarkable energy product. It is uniquely reliable (30 years plus), highly efficient, environmentally benign, and can be manufactured with costs permitting fully economic photovoltaics to be used for U.S. peaking and intermediate power, and for stand-alone power in remote sites.

The DOE/JPL FSA Project is one of the more successful, cost effective, Government/university/industry, technology-development efforts in the history of U.S. Federal support of technology.

Maycock concluded with the statement that he was proud to have had a small role in management of the JPL/FSA Project and he joined the industry in saying, "Well done!"

Roger Little, of Spire Corp., presented an historical overview of the progress of photovoltaics as a function of oil price and DOE PV budgeting levels. He reviewed the state of the worldwide PV industry, the PV interests and activities of utilities, and the phases of evolution that a technology such as photovoltaics goes through on the way to commercialization. Although he has lengthened his estimate of the time it will take for photovoltaics to evolve from discovery to commercialization to an interval of from 50 to 80 years, Little's remarks were optimistic. He indicated that PV manufacturers must be patient because the markets for photovoltaics are coming, they are growing, and they are very real.

Overviews of national PV activities, and how the FSA Project fits into those efforts, were followed by eight summaries regarding specific technical efforts of the Project. These included accomplishments, lessons learned, and potential and continuing R&D needs.

In his review of the Silicon Material Task efforts, Jim Lorenz, consultant, stated that worldwide attention was attracted to the JPL/DOE Project because of the quality of the processes in the Task, which is a prime example of the proper use of Government funding of high-cost, high-risk R&D. The Task provided a technology base for a possible silane-to-silicon deposition process.

This Task resulted in the development and commercialization of a novel process for making silane and high-quality semiconductor-grade polycrystalline silicon [Union Carbide Corp. (UCC) silane-to-silicon process], and ensured adequate capacity in the United States for pure silane for the DOE/Solar Energy Research Institute (SERI) amorphous-silicon (a-Si) R&D program and for future production. The United States has a leadership role in the production and use of pure silane and pure polysilicon.

The UCC process has the potential to provide the most pure polysilicon for photovoltaics or semiconductor use. Silicon technologies of value to the worldwide electronics industry have been established and published.

Substituting for F. Wald, J. Kalejs, Mobil Solar Energy Corp., reviewed the technical progress made in the Silicon Sheet Growth Program during the 11 years of the DOE/JPL FSA Project. In 1976, when the Program began, there were nine proposed techniques to produce silicon ribbon. By 1980, this number had decreased to three techniques. At present, in 1986, only two of the techniques have survived to the start-up, pilot-plant stage in industry. These two are the edge-defined, film-fed growth (EFG) technique, developed by Mobil Solar Energy Corp. that produces closed shape polygons, and the WEB dendritic technique developed by Westinghouse Electric Corp. that produces single ribbons. Kalejs discussed both the status and future concerns of the EFG and WEB techniques.

Two other silicon-sheet growth techniques are available to industry: Low-Angle Silicon Sheet (LASS) developed by Energy Materials Corp. (EMC), and Edge-Stabilized Ribbon (ESR). Other silicon-sheet processes are being developed in France, Japan, and West Germany.

In his review of High-Efficiency Silicon Solar Cells A. Rohatgi, Georgia Institute of Technology, reported that the first solar cells, fabricated in 1954, were only 6% efficient. By 1960, because of impetus for improvement from the U.S. space programs, solar cell efficiencies had climbed to 10 to 12%. In 1975, when the FSA Project began, space solar cell efficiencies had increased to 14 to 15%. Today, the Point-Contact Solar Cell, developed at Stanford University under a FSA contract, has an efficiency of 22.2%, close to the theoretical maximum efficiency of about 25%.

Rohatgi discussed various parameters that affect solar cell efficiency. It is not understood why solar cells produced from less expensive Czochralski (Cz) silicon are less efficient than cells fabricated from more expensive float-zone (FZ) silicon. Performance characteristics were presented of recently produced, high-efficient solar cells fabricated by Westinghouse Electric Corp., Spire Corp., University of New South Wales, and Stanford University.

Don Bickler, JPL, discussed the major processes involved in production of crystalline-silicon solar cells: surface preparation, junction formation, metallization, and assembly. The status of each of these processes, and the sequence in which these processes are applied, were described as they were in 1975, as they were in 1985, and what they may be in the future. Bickler pointed out that, from 1975 to 1985, progress in lowering the cost of solar cell processing has reached a plateau, that emphasis today is on improvement of cell efficiencies, and that any new cell designs proposed in the future will require development of new production processes and sequences.

P. Willis, Springborn Laboratories, Inc., presented a detailed summary of the diverse encapsulation materials and techniques that evolved to meet the cost-goals of the FSA Project. A "typical" solar cell now consists of low iron glass, two layers of ethylene vinyl acetate (EVA) polymers, a porous spacer, primers/adhesives, a back cover of Tedlar, and a gasket/seal for a volume cost of $1.30/ft$^2$. This compares well with the Project's original goal of $1.40/ft$^2$. Willis concluded that the FSA Project resulted in high-performance, cost-effective encapsulation systems for PV modules.

Evolution of the design and reliability of solar modules was described by R.G. Ross, Jr., JPL. Design requirements of modules involved 14 different considerations, including residential building and material electrical codes, wind-loading, hail-impact, and operating temperature levels, module flammability, and interfaces for both the array structure and the operation of the system.

Reliability research involved 11 diverse investigations including glass-fracture strength, soiling levels, electrochemical corrosion, and bypass-diode qualification tests. Based on these internationally recognized studies, and performance assessment and failure analyses, the FSA Project in its 11-year duration served to nurture the development of 45 different solar module designs from 15 PV manufacturers.

In his summary of solar module evolution, C. Gay of ARCO Solar, Inc. pointed out that although laboratory testing may yield acceptable results, the credibility of the usefulness of PV energy depends upon performance of modules in the field. The 6.5 MW Carissa Plain installation by ARCO has performed extremely well both in predicted delivery of electrical energy and in reliability. Warranty replacements of modules are running less than one module out of every 25,000 modules.

An economic-analysis summary of the manufacture of crystalline-silicon modules involving silicon ingot/sheet, growth, slicing, cell manufacture, and module assembly, was presented by H.L. Macomber, a consultant. Economic analyses provided:

(1) Useful quantitative aspects for complex decision-making to the FSA Project.

(2) Yardsticks for design and performance to industry.

(3) Demonstration of how to evaluate and understand the worth of an R&D activity both to JPL and to other Government agencies and programs.

Macomber concluded that future R&D funds for PV energy must be provided by the Federal Government because the solar industry today does not reap enough profits from its present-day sales of PV equipment.

Following the morning presentation of eight summaries dealing with crystalline-silicon photovoltaics, a panel of seven participated in an afternoon session dealing with "Recommendations for Crystalline-Silicon in the DOE's Five-Year Photovoltaic Research Plan." Chairman of the panel was R. Annan of DOE.

In his introductory remarks, R. Annan pointed out a series of present-day paradoxes. Although a strong policy statement has been made for the pursuit of PV energy, the budgetary response has been poor. And, although a strong scientific and engineering partnership exists among PV industrial companies, universities, and the Federal Government, Federal funding remains below required levels. Photovoltaic technologies are strong, but the markets for PV products are weak. The development of PV energy is a long-term affair, but it is faced with short-term politics.

John Day, Strategies Unlimited, discussed the changes that have taken place in the PV industry during the 11-year period of the FSA Project. In 1975, when the Project began, 95% of the PV industry's cash flow came from the Federal Government, the Government was the only purchaser, and the industry was run by individualistic entrepreneurs operating under-financed small ventures. By contrast, today, the Federal Government provides only 25% of the industry's cash flow, there are commercial purchase besides the Government, and the industry now is run by planning teams operating in well-financed industrial companies.

As for the future, Day indicated that for the next 5 to 10 years, photovoltaics will continue to be used to generate power in remote locations. Beyond 10 years, there will be an increase in grid-connected PV applications. His recommendations for Government PV-policy for the next 5 years are:

(1) Give assistance in the export of PV equipment.

(2) Provide education about PV energy to electrical utilities.

(3) Provide for long-term research efforts.

G. Smith, U.S. Navy, stated that the U.S. Department of Defense (DOD) is the largest single consumer of energy in the United States, annually using about 250 million barrels of oil equivalent (MBOE). Of this, 70% is provided by petroleum products. A renewable energy source such as photovoltaics, therefore, can play a major role in DOD energy-management objectives, specifically in programs aimed at petroleum substitution in shore facilities. The latter accounts for about 25% of DOD's total energy budget. Thus, DOD, potentially, can be a several billion dollar per year market for the PV industry.

Through the Federal Photovoltaics Utilization Program (FPUP), the DOD installed 218 diverse PV systems that ranged in size from a few watts to 56 kW. The Navy, which now serves as the lead service within DOD for PV-system activities, has identified 21,000 cost-effective applications for photovoltaics throughout the service.

In an effort to expand PV-use more aggressively throughout DOD, a tri-service Photovoltaics Review Committee (PRC) was formed in December 1985 with the following partial list of 5-year objectives:

(1) To study ways of identifying potential PV applications within DOD.

(2) To reduce overall costs of DOD PV-related products.

(3) To transfer technical information about photovoltaics throughout the military.

(4) To promote widespread application of PV systems in the three service branches.

Smith outlined six activities being considered by the .RC, one of which is sponsorship of a joint industry/DOD meeting at which there would be a free exchange of information on the PV needs of the various services. The DOD is a lead agency and an active participant of the Committee on Renewable Energy Commerce and Trade (CORECT).

Speaking as a representative of an electrical utility, K. Firor of Pacific Gas and Electric (PG&E) indicate that a utility must balance the benefits of photovoltaics (free fuel, modularity, minimal water use, short lead times, few moving parts, peak load match, minimal environmental inpact, and political and social acceptance) against the obstacles to a utility's use of photovoltaics (high costs, fear of the unknown, unknown O&M costs, unknown O&M procedures, unknown reliability, unknown power quality, and unfamiliarity of the technology). She pointed out that just because R&D people know how to handle photovoltaics does not mean that a utility will build a solar power plant. She presented a diagram that detailed a realistic view of the many inputs required by a utility company's management before a decision can be made to build a PV power plant.

According to E.L. Ralph, Hughes Aircraft Company, there is no clear superiority among thin films, multi-bandgap cells, and crystalline silicon, if balance-of-system costs, reliability, and efficiency are considered. Crystalline-silicon technology, however, has several factors in its favor: a proven database, proven advances waiting to be incorporated into commercial production, and potential for considerable future advances.

Ralph feels that DOE support for the Crystalline-Silicon Program is dangerously low. His recommendations for the Program are:

(1) Need for a production technology to lead to modules with 15% efficiency.

(2) Need for a research program to lead to flat modules with 18% efficiency.

(3) A research program with multi-bandgap (silicon-based) cells to yield flat modules with 25% efficiency.

Ralph presented a list of crystalline-silicon research needs that included the following:

(1) Sheet growth: crystal quality, automatic growth, and high-throughput.

(2) Minimization of surface losses: physical/chemical structures, surface properties, and methods.

(3) Measurements: lifetimes, mobilities, and recombination at surfaces and interfaces.

(4) Process development: attainment of low-cost processes compatible with high-efficiency.

K.M. Koliwad, JPL, stated that crystalline-silicon technology can meet the long-range objectives of the DOE PV Program. Future research should focus on the solution of fundamental problems to permit the production of high-quality silicon sheet, and on the advance of knowledge of basic mechanisms of charge-carrier losses to allow the production of large-area, high-efficiency solar cells on low-cost silicon sheet.

Koliwad recommended:

(1) An emphasis of fundamental and generic research to benefit a large segment of the PV industry.

(2) A balance among various technology options and a balance among industry, university, and Federal laboratories.

(3) Development of a mechanism for longer-term support to universities.

(4) Establishment of a formal procedure to transfer technology from research to applications.

(5) Use of DOD and other support for leverage in related areas.

C. Rose, of Westinghouse Electric Corp., presented a summary of dendritic web technology. In December 1984, web growth was 9000 $cm^2$/week/furnace with a module efficiency of 13%. By December 1985, web growth and module efficiency had increased to 47,000 $cm^2$/week/furnace and 14%, respectively. Rose discussed research requirements for high-speed, silicon ribbon growth, requirements for silicon materials, and requirements for flat-plate collectors.

E.E. Daniels, Solarex Corp., summarized the accomplishments of the PV industrial community. With respect to the four silicon-technology options (single crystal, semicrystalline, amorphous, and ribbon), Daniels showed a diagram that depicted Cz and semicrystalline silicon accounting for 65 and 35%, respectively, of the PV market in 1984.

But, by 1991, the Daniels-diagram predicts a market made up of semicrystalline silicon (46%), amorphous silicon (38%), Cz silicon (6%), silicon ribbon (5%), and other silicon technologies (5%).

INDUSTRY-USERS DAY SUMMARIES

Following the plenary sessions of the first day, and the three parallel technical sessions of the second day, the third morning of the 26th PIM was devoted to a novel session called Industry-Users Day. Representatives from 14 diverse organizations presented brief, informal discussions of present-day activities in the evolving field of photovoltaics.

R. Johnson, Strategies Unlimited. In spite of present-day pessimism because of foreign competition, loss of tax benefits, and cutbacks, the future looks optimistic as markets for photovoltaics continue to grow. North America is the largest single consumer of PV power modules.

W. Breneman, Union Carbide Corporation. The Electronics Division of UCC now has a Polysilicon Department producing silicon from extremely pure silane in plants at Washougal and Moses Lake, Washington, with production being 100 and 2400 MT/year, respectively. A 3000 MT/year plant is planned, using fluidized-bed reactors (FBRs). As yet, no location for this plant has been selected.

A. Morrison, Kayex Corp.. Substituting for Dick Lane, Andy Morrison stated that Kayex Corp., a subsidiary of General Signal, prepares economically viable silicon by an advanced Cz technique.

D. Jewett, Energy Materials Corp.. Jewett revealed that EMC now has a low-angle silicon sheet process that operates with continuous replenishment and high-speed growth. The EMC process will be offered to industry with a pilot-plant capability within a year.

F. Schmid, Crystal Systems. Schmid expects that the 100 x 100 mm silicon wafers will be around for the next 10 years. The heat-exchange method (HEM) technique for the growth of silicon ingots needs more R&D to increase its throughput. Wafers are prepared from low-cost silicon by HEM ingot-growth and slicing of the ingots by the fixed abrasive slicing technique (FAST).

E. Sachs, A.D. Little Company. Sachs described 12 man-years of development of ESR at A.D. Little Company (ADL). Use of a single-ribbon, melt-replenished furnance, operated 100 h continuously (three-shift operation, 96% duty-cycle) to produce 62,000 $cm^2$ of silicon ribbon, yields silicon that is fabricated into solar cells with 12.7% efficiency.

K.V. Ravi, Mobil Solar Energy Program. Ravi described the EFG process for production of closed-shape, thin-shelled polygons of silicon ribbon. A photo was shown of a 20-ft-high nonogon of silicon and a hexagon with 4-in.-wide sides. Mobil believes that the EFG process is the only silicon-ribbon technology that will make photovoltaics economically feasible. The EFG-produced silicon ribbon routinely yields solar cells of 14% efficiency.

C. Rose, Westinghouse Electric Corp.. In 1980, Westinghouse transferred its dendritic web ribbon process from R&D to a pilot-plant installation. Cuts in funding by the Reagan Administration, however, threw the program into confusion. Recently, Westinghouse decided to change its pilot-plant line to a manufacturing mode to demonstrate the cost of the project. When those figures have been obtained, Westinghouse will make a decision whether to continue with the development of the process.

L. Kashar, Scanning Electron Analysis Laboratories. Kashar explained what instruments the Scanning Electron Analysis Laboratories (SEAL) had available to carry out microanalysis of PV cells. Such information can provide valuable data concerning the relationships between contaminants and cell performance.

C. Gay, ARCO Solar. Crystalline silicon has been the mainstay of PV-cell production, while R&D proceeds for thin-film cells. Although single-crystal PV cells now produce electricity for about $5/$W_p$, they must get down to $0.50/$W_p$ to compete with coal and nuclear power plants.

J. Goldsmith, Solarex Corp.. Solarex, which is a wholly-owned subsidiary of American Oil Company (AMOCO), has a heavy investment in a-Si and thin films. More work is needed. Thus, the continuation of FSA-type projects is necessary for the development of a viable, U.S. national resource.

I. Shahryar, Solec International. Solec has become a specialty manufacturing house, turning out 10 to 12% efficient solar cells to fit a specific customer's desires.

M. Spitzer, Spire Corp.. Substituting for Roger Little, Mark Spitzer described Spire's worldwide activity in the development of automated equipment for the production of solar modules and ancillary solar equipment.

W. O'Neill, AEG. AEG, purchased by Mercedes-Benz and having links to Telefunken, has offices in 103 countries and operating solar systems in 55 countries. The company has 90 years experience in DC motors and DC appliances. AEG uses semi-crystalline silicon to fabricate pliable, flexible modules with glass encapsulant and stainless steel framing. Folding solar modules are made for military use. AEG also makes balance-of-system components: charge regulators, inverters, and charge controllers for hybrid installations (wind/PV and wind/PV/diesel). AEG, with offices in Somerville, New Jersey, and Phoenix, Arizona, can offer 100 kW solar arrays.

K. Firor, Pacific Gas & Electric. In an attempt to advance education about photovoltaics to utilities, PG&E now is involved in a project called Photovoltaics for Utility Service Applications (PVUSA). The PVUSA program consists of the installation of 10 MW capacity during a 10-year period at two different sites, each with different insolations. The program will proceed in two phases:

Phase 1 (1986 to 1990) will lead to an installation of 3.5 MW at each site. This will cost $14.5 million, of which 37% will be provided by PG&E, DOE will provide 50%, and the Electric Power Research Institute (EPRI) will provide remaining 13%.

Phase 2 (1990 to 1994) will lead to an installation of a 1 MW, PG&E-designed plant at the insolation site, and a 0.5 MW, PG&E-designed plant at the direct insolation site. DOE will provide $20 million and PG&E will provide $14.5 million.

# INTRODUCTION TO PROCEEDINGS

JET PROPULSION LABORATORY

W. T. Callaghan

W. T. Callaghan, Manager of the Flat-Plate Solar Array (FSA) Project, opened the 26th, and last, Project Integration Meeting (PIM) by welcoming the participants

In his remarks, he reviewed the accomplishments made, the dedication shown by the many firms, universities, and persons who have been involved in the FSA Project. "Like so many long-term relationships in life, FSA is a difficult one to end. We can all be very proud of our role in helping to reduce prices by a factor of 15, we can point to module efficiency increases of a factor of 3, and we can cite 10-year warranties now where there were none before."

He also cited reduced fossil fuel energy prices, lessened public interest in long-term energy planning, and increased foreign photovoltaic (PV) programs as the challenges facing U.S. PV firms.

A long-term goal was accomplished by the FSA Project when Callaghan introduced the audience to the Spire Corp. 15.2% AM 1.5, 75.2 W module (STC, global spectra) that had just been tested by FSA. The module was developed under contract to FSA by Spire Corp. and represents the first, full-sized 15% flat-plate crystalline silicon PV module ever made.

In recognition of their contributions to the success of the FSA Project, Callaghan cited Mrs. Mary J. Phillips and Mr. Elmer Christensen from the FSA Project Office. In addition, commemorative plaques were presented to Mr. Robert Forney (JPL), Mr. John Goldsmith (Solarex Corp.), and Dr. Morton Prince, U.S. Department of Energy (DOE), for their invaluable contributions to the development of photovoltaic science.

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C-2

# DOE COMMENTS

## U.S. DEPARTMENT OF ENERGY

M. Prince

Today is an exciting day for me and I believe for many individuals associated with the FSA Project. Many of the original objectives of the Project have been accomplished and several objectives are close to meeting their goals. All of this was accomplished with much less than 1/2 of the originally planned budget, especially when adjusted for the inflation that we have had during the past 11 years.

I am not exactly sure what Paul Maycock and Roger Little are going to say. But I am apologizing to them now if I preempt them.

In preparing my comments, I went back to some early JPL documents to see what was originally proposed and how well these objectives were met. The first meeting I attended was the Industrial Briefing of February 5, 1975 which kicked-off the Low Cost Silicon Solar Array Project which eventually evolved into the Flat-Plate Solar Array Project. That meeting was held simultaneously up at the Von Karman Auditorium at JPL and at a NASA Auditorium in Washington using a secured communication line.

Many of the original participants and attendees of that briefing are here today. I would like to quickly run thru four slides of that briefing.

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SLIDE 1 SHOWS THE ORIGINAL ORGANIZATION OF THE PROJECT WITH THE FIVE TECHNICAL TASKS SUPPORTED WITH AN ANALYSIS AND INTEGRATION STAFF. ALL THE ORIGINAL MANAGERS EXCEPT RALPH LUTWACK HAVE GONE ON TO OTHER ACTIVITIES.

SLIDE 2, SHOWS THE ORIGINAL OBJECTIVE OF THE SI MATERIAL TASK OF $35/KG FOR RAW-STOCK SI. TODAY IN 1975, $ WE ARE WAY AHEAD AT THAT OBJECTIVE AND WITH THE UNION CARBIDE WORK ON THE FBR, WE EXPECT THAT WE WILL CUT THE COST SIGNIFICANTLY FURTHER IN THE NEAR FUTURE.

SLIDE 3 SHOWS THE ORIGINAL OBJECTIVES ~~AT~~ OF THE LARGE AREA SILICON SHEET TASK. ALTHOUGH WE HAVEN'T MADE THE PRODUCTION TYPE OBJECTIVES. WE HAVE REACHED THE HIGH EFFICIENCY MODULE GOAL WITH 13% AVAILABLE COMMERCIALLY AND 15% MADE IN THE LABORATORY.

SLIDE 4 SHOWS THE OBJECTIVES AT THE MODULE ENCAPSULATION TASK. HERE WE HAVE MEET THE OBJECTIVE QUITE WELL.

THE AUTOMATED SOLAR ARRAY ASSEMBLY TASK AND THE LARGE SCALE PRODUCTION TASK ALSO HAD OBJECTIVES THAT WE COULD NOT MEET BECAUSE OF BUDGET LIMITATIONS AND CHANGES IN WHAT THE GOVERNMENT COULD DO FROM A PROGRAMMATIC POINT OF VIEW.

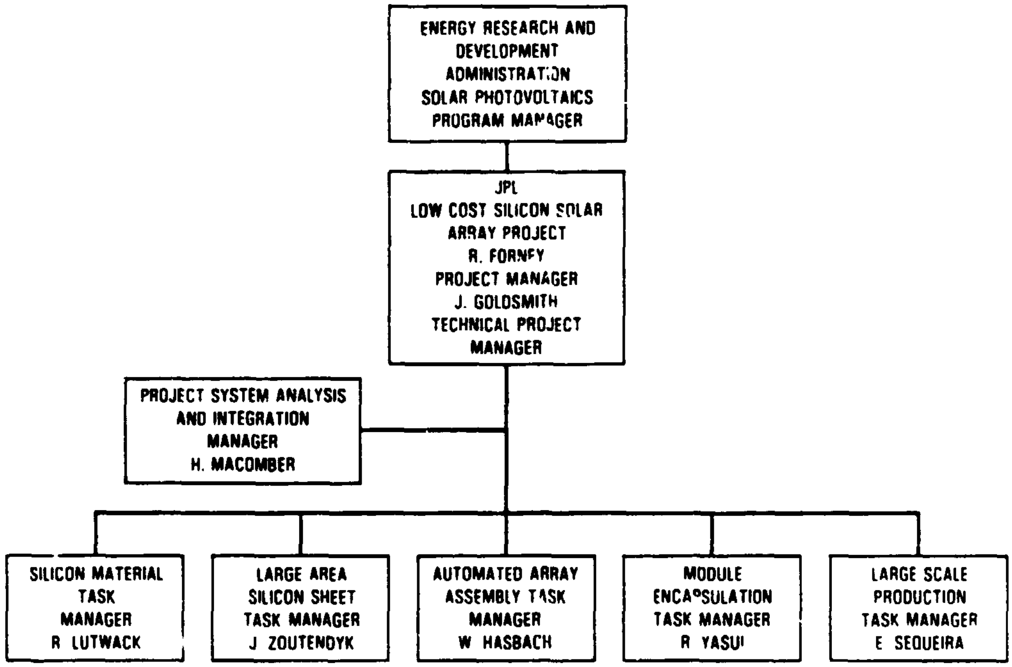
About a year later we had our first PIM with about 20 contractors in mid-January 1976. At that time we had a first overall review and smaller task meetings. That meeting set the excellent tone for the future integration meetings of which this is the last for the FSA Project.

Another early sheet that I found interesting is the original Project budget requirements of over $650M for ten years and the first revision which was made after our FY 1976 budget figures came out. This extended the project from 10 to 12 years at about the same overall budget level. It is interesting to note that the FSA Project has spent $228M thru February of this year and will probably complete its activity with expenditures under $235M. This will be less than 36% of the original budget even without taking inflation into account. Many of the expensive items in the original plan such as the production pilot lines and the multi-megawatt buys were eliminated from the project. But in spite of these reductions in scope, the Project has been successful financially as well as technically. Part of this accomplishment is due to you in industry as you have been willing (rightfully so) to cost-share many of the more expensive items and I want to thank you for your contributions to our success.

Finally since today we will be hearing where we are coming from, where we are, and where industry is going to be, I thought I would put my views before you. In my last Slide I have listed some key technology parameters for the single crystal silicon technology with my beliefs as to what the status was, is and will be. As you see I believe that we have reached most of the ultimate technology end points. However, we still have some improvements possible with silicon such as improved efficiencies and improved understanding of ribbon technology. We at DOE believe these are still worth pursuing and hope to have JPL with their strong in-house technology groups help us make these improvements.

Low Cost Silicon Solar Array Project

## JPL PROJECT ORGANIZATION




Low Cost Silicon Solar Array Project

## SILICON MATERIAL TASK

### TASK OBJECTIVES

- **Production**
  - **Establish process with high volume production capability**
  - **Demonstrate suitability for meeting 1985 goal equivalent to 500 MW of modules per year**
- **Price**
  - **Demonstrate energy use and economic effectiveness**
  - **Obtain production price of < $35 per KG**

Low Cost Silicon Solar Array Project

## LARGE AREA SILICON SHEET TASK

- Large area low cost silicon sheets
  (< $1.60/sq ft)
- Silicon sheets with high photovoltaic efficiency
  ( >10% terrestrial array efficiency)
- Automated sheet production capability
  ( >50 million sq ft/yr)

Low Cost Silicon Solar Array Project

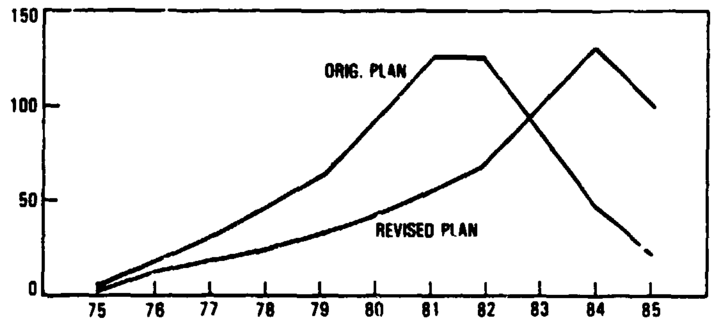
## MODULE ENCAPSULATION TASK

- Near Term Objective
  - Select the best candidate encapsulation material and process for integration into the automated array task by 1978
- Long range objective
  - Develop, test and qualify encapsulation materials and processes for arrays with a design operating lifetime greater than 20 yr

Low-Cost Silicon Solar Array Project

## CURRENT TEN-YEAR SUMMARY — OBLIGATIONS REVISED BUDGET COMPARISON

| | 75$ | | | 77$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $ MILLIONS FY | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 | 84 | 85 | TOTAL |
| ORIG. PLAN | 3.0 | 16.1 / 6.4* | 30.2 | 46.2 | 62.3 | 91.2 | 124.0 | 124.0 | 84.2 | 47.0 | 22.0 | 656 6 |
| REVISED PLAN | 3.0 | 12.4 / 3.5* | 18 | 24 | 32 | 42 | 54 | 68 | 100 | 130 | 100 | 586.9 |




*TRANSITION PERIOD FUNDS

Low-Cost Silicon Solar Array Project

## JPL/FSA PROJECT ACCOMPLISHMENTS

- **<u>General</u> — DOE (and ERDA) funded activities at JPL has made possible a nascent industry making terrestrial photovoltaic cells, modules and systems ($200 M/year). The Project's findings has helped the U.S. semiconductor industry with technology development as well.**
- **<u>Specific Technology Developments</u>**

| Parameter | 1975 Status | Present Status | Near-Future Status |
|---|---|---|---|
| Rawstock Material | $60/Kilogram | $40/Kilogram | $20/Kilogram |
| Silicon Crystal Size | 3" Diameter | 6" Diameter | 8" Diameter |
| Crystal Slicing | O.D. Saws | Multiple Wire, Multiple Band and Large I.D. Saws | Multiple Wire, Multiple Band and Large I.D. Saws |
| Ribbon Technology | EFG | EFG, Dendritic Web, ESP, RTR | EFG, Dendritic Web, ESP, RTR |
| Junction Formation | Two Diffusions | Simultaneous Diffusion, Ion Implantation Plus Anneal | Simultaneous Diffusion, Ion Implantation Plus Anneal |
| Contact Formation | Evaporation | Evaporation, Silk Screen Printing, Laser Deposition | Evaporation, Silk Screen Printing, Laser Deposition |
| Assembly of Cells | Hand Assembly | Automatic Stringing Equipment | Automatic Stringing Equipment |